ARTICLE IN PRESS

CSNDT:31

Case Studies in Nondestructive Testing and Evaluation ••• (••••) •••–•••

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Case Studies in Nondestructive Testing and Evaluation

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ISO test survey on material influence in dimensional computed tomography

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ARTICLE INFO

Article history:
Available online xxxx

ABSTRACT

ISO/TC 213/WG 10 is responsible for creating international standards (series ISO 10360) for the acceptance testing of coordinate measuring systems (CMSs). A current topic is creating a future part of ISO 10360 for CMSs using dimensional computed tomography (CT). The discussion is focussed on how to include material thickness influence in acceptance testing. ISO/TC 213/WG 10 decided to perform an experimental survey to study this topic. This ISO test survey covers several national metrology institutes and manufacturers. Reference standards under study made of aluminium are two step cylinders provided by the National Metrology Institute of Japan (NMIJ), and two hole plates provided by the Physikalisch-Technische Bundesanstalt (PTB), Germany. To check for residual errors of CT-based CMSs, additional reference standards may be measured by participants. This report details results and experiences of the participant PTB. PTB applied scaling reference measurements of a multi-sphere standard and a printed circuit board as additional reference standards, i.e. in addition to hole plate and step cylinder measurements, respectively. Measurements were performed in mid 2015 using the PTB dimensional CT system (Nikon Metrology MCT225). In this contribution, special focus is placed on the interpretation of the results and the consequences of a potential testing regime. This text does not directly describe an existing ISO standard nor a published or intended ISO standard draft. It is intended to contribute to the research of influence parameters which are relevant for a possible future part of ISO 10360 for the case of CT-based CMS (which is assumed to be part 11).

1. Introduction

The international standards series ISO 10360 describes procedures for the acceptance and reverification testing of coordinate measuring systems (CMSs). Since 2010, the development of a possible future part of ISO 10360 for CMSs using dimensional computed tomography (CT) is an objective of a task force of ISO/TC 213/WG 10 – the technical committee which creates standards of the ISO 10360 series. At the moment it is assumed that this future part of ISO 10360 will get – after successful creation and balloting – the identification ISO 10360-11. But this preliminary assignment may be changed by ISO during the process. Acceptance testing of industrial CT systems dedicated to coordinate measurements (i.e. performing dimensional CT) shall follow the same principles, which have been accepted for an ISO 10360 series test and are common for tactile and optical CMSs. One principle which shall be implemented is to include all dominant error sources and additionally to assess errors of CT-based CMSs as bidirectional length measurement errors. These principles result partly from

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http://dx.doi.org/10.1016/j.csndt.2016.04.001
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Fig. 1. Mandatory reference standards inside the ISO test survey (left): PTB hole plate Al2 size 48 mm × 48 mm × 8 mm with 28 holes of 4 mm in diameter and NMIJ step cylinder SC1 with maximum outer diameter of 50 mm and central hole 8 mm in diameter inside PMMA enclosure. The middle and right images show optional scaling reference standards: multi-sphere standard Metrotom Check Micro with outer diameter of 75 mm (courtesy of Carl Zeiss) and PTB-calibrated printed circuit board (PCB) 100 mm × 160 mm in size.

the output and discussions prior to a first test survey that was conducted by ISO/TC 213/WG 10 between the end of 2013 and early 2014, which has only been published to some extent [1,2]. One purpose of this first test survey was to test the feasibility of using hole plates (see, e.g., [3]) to measure length measurement errors of CT-based CMSs. While the feasibility in using hole plates was shown to some extent, it turned out that additional outer material (e.g. shells) does not seem to be required for acceptance testing.

At the moment, the important material (thickness) influence in the acceptance testing is under discussion. A dependency of the measurement errors with respect to the thickness and the material to be penetrated is mainly caused by two reasons. First, X-ray absorption of polychromatic radiation does not follow Beer's law. Second, the scatter background increases with larger object size and with penetrated material thickness. After tomographic reconstruction the calculated density is increasingly inhomogeneous and the edge profiles smeared over which produces errors in the surface determination process. Whereas it is agreed in general that the penetration of massive material (high thickness and high thickness variation) can have a significant effect on dimensional CT measurements, the implications for test scenarios for a possible ISO 10360 length measurement error testing are not agreed upon. Thus, ISO/TC 213/WG 10 is interested in investigating and comparing the material effects shown in two proposed approaches for performing the length measurement error test: (1) Use of multi-sphere standard (which does not include material thickness influence) and step cylinder (to test the material thickness influence) in two consecutive tests and (2) the use of hole plate alone (to include all relevant effects in one test). ISO/TC 213/WG 10 decided to perform a new test survey to study the material thickness influence based on these two approaches and, finally, to perform an analysis of the whole testing scenario, also including other aspects (e.g. overall effort, costs, ease of use, calibration). The whole ISO test survey performed in mid 2015 covers several national metrology institutes (NMIs) and several manufacturers of CT-based CMSs. This paper reports on measurements the Physikalisch-Technische Bundesanstalt (PTB) has performed.

2. The ISO test survey: reference standards in use

Mandatory reference standards in use by the test survey participants are two step cylinders (SC) provided by the National Metrology Institute of Japan NMIJ, AIST, and two hole plates (HP) provided by PTB, Germany. Fig. 1, on the left, shows the specimen hole plate identification PTB Al2 and step cylinder identification NMIJ SC1 which PTB has measured. All standards are made of lead-free MgSi aluminium alloys (PTB hole plates A6082, NMIJ step cylinders A6061). The composition of these two alloys is similar, but not identical. The absorption of the SC's material is about 10% higher – for the parameters chosen here – compared to the hole plate. We do not expect a negative effect from this for the test survey. The standards itself have been manufactured using industrial approved manufacturing technologies (1) electrical discharge machining (EDM) of the hole plate cylinders and (2) precision milling for the case of the step cylinder. No further roughness reducing step has been applied. For an independent traceable scale correction and to include this in the data interpretation, additional measurements of two calibrated reference standards were performed by PTB only: of a well-known multi-sphere standard (MS) (Fig. 1, middle) featuring 22 ruby spheres mounted on aluminium oxide ceramic shafts and of a printed circuit board (PCB) (Fig. 1, right). The PCB used here is made of a polyimide/glass fibre composite with ring-shaped metal pads arranged in a 38 × 61 matrix at a distance of 2.54 mm. It has a copper layer 35 µm thick. The pad centre positions are calibrated.

Length measurements in this ISO test survey were performed in conformance with the technical guideline [4], which was created by NMIJ and PTB and agreed upon in ISO/TC 213/WG 10. Measurements of both mandatory reference standards are to be performed in two orientations relative to the axis of rotation: vertical 0° position and 45° tilted position (see Fig. 2 showing the specific PTB mounting).

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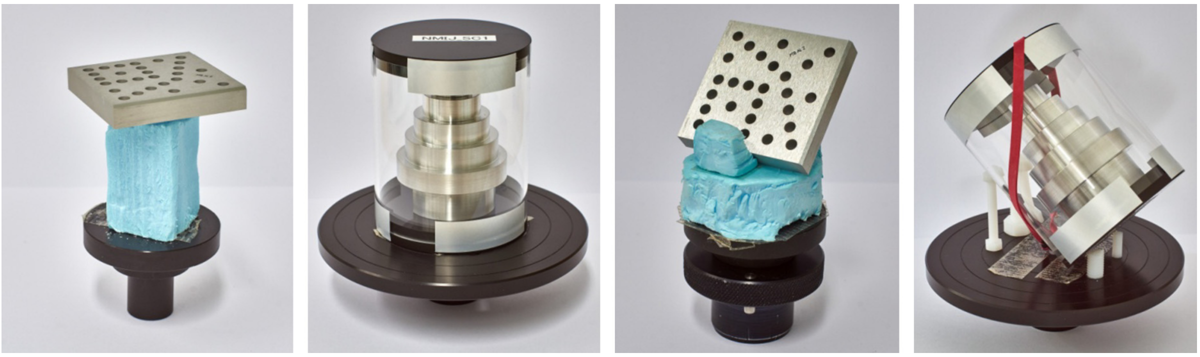

Fig. 2. Reference standard mounting in the two vertical (0°) and two tilted (45°) measurement positions. The blue hard foam visible for mounting the hole plate has very low X-ray absorption while being stable and elastic to prevent movements of the body. Shear forces caused by double-sided adhesive tape are avoided, as they would produce creeping. Thus, hole plate measurements are not impaired by this mounting.

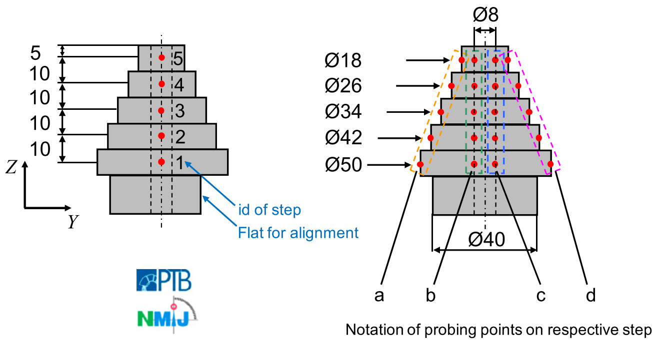

Fig. 3. Lengths to be measured on step cylinder (simplified sketch taken from [4]; dimensions in mm).

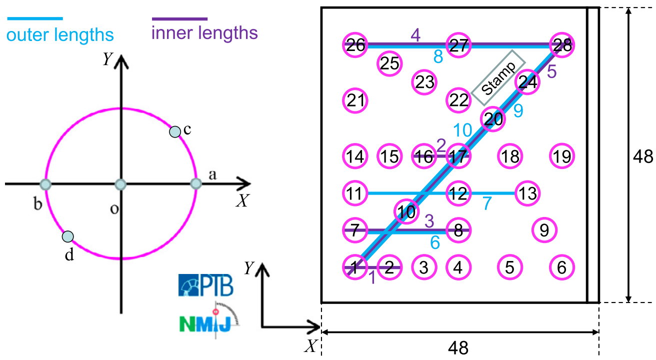

Fig. 4. Lengths to be measured on hole plate on the right (simplified sketch taken from [4]; outer dimensions in mm). Measurement of hole plate is performed near the middle plane (plate thickness 8 mm). Hole plate features a bevel on top right side and an identification stamp. Diagram on the left shows the location of probing points a–d inside each hole (e.g. point id 7b indicates point b at hole No. 7).

3. The ISO test survey: measurands under study

According to [4], ten bidirectional lengths L shall be measured on each standard – five outer/outside lengths and five inner/inside lengths (Figs. 3–4 and Tables 1–2). All measurements shall be repeated once to allow a tracking of repeatability issues of the CT system in use. This concept is a compromise between total effort and sensitivity of the test. Furthermore, it must be stressed that the objective of this ISO test survey is to analyze the systematic effects related to material thickness in CT, and not to benchmark CT systems among participants. Note, that for both mandatory reference standards and for all measurement positions no X-ray projections are acquired where an "attenuation-free view" through the holes for the case of the HP or for the single hole of the SC is performed.

Table 1
Nominal lengths L to be measured on step cylinder.

Step cylinder (10 bidirectional lengths in total)				
	Length id	Point id1	Point id2	L in mm
Inside measurements	1	5b	5c	8.00
	2	4b	4c	8.00
	3	3b	3c	8.00
	4	2b	2c	8.00
	5	1b	1c	8.00
Outside measurements	6	5a	5d	18.00
	7	4a	4d	26.00
	8	3a	3d	34.00
	9	2a	2d	42.00
	10	1a	1d	50.00

Table 2
Nominal lengths L to be measured on hole plate.

Hole plate (10 bidirectional lengths in total)				
	Length id	Point id1	Point id2	L in mm
Inside measurements	1	1b	2a	10.00
	2	16b	17a	10.00
	3	7b	8a	22.00
	4	26b	28a	40.00
	5	1d	28c	54.91
Outside measurements	6	7a	8b	14.00
	7	11a	13b	26.00
	8	26a	28b	32.00
	9	1c	24d	38.43
	10	1c	28d	46.91

4. PTB agenda inside this test survey

The PTB agenda inside this test survey is to study the material thickness influence in CT acceptance testing and to draw conclusions as to how future ISO 10360 acceptance testing for CT can be implemented. It is known from previous works that a proper beam hardening (BH) correction is important for performing dimensional CT measurements (see, e.g., [5] for a critical discussion on real CT measurements and, e.g., [6] for simulated CT measurements). To this end, PTB analyzed the impact of a reasonable BH correction on measured lengths L. This approach was suggested several times by ISO/TC 213/WG 10 members to provide information about the material thickness impact on real dimensional CT measurements, whereas for simulated CT measurements also an analysis of the differences between monochromatic and polychromatic radiation remains possible (see, e.g., [7]). For the reference standards in this study made from aluminium and for aluminium workpieces of similar size and penetration lengths, frequently a moderate BH correction provides improved results. For this reason, a BH correction of moderate strengths (preset of lowest BH correction strength in software in use) was applied. For making effects traceable within this ISO test survey the same BH correction was either applied to both standards (which feature comparable maximum penetration lengths) or switched off for both standards (see results in section 11). Furthermore, PTB studied a potential scaling error as a disturbing effect, as reference will be made to calibration data traceable to the SI unit of length.

For a final evaluation of the two approaches (multi-sphere standard + step cylinder as first and hole plate as second) PTB will consider also "secondary" aspects which are however very important to the industrial use: e.g. overall effort (time and costs), ease of industrial use (applicability of concept, operator requirements, risk of application errors), calibration aspects (effort for calibration and calibration abilities). Here from the beginning the concept of using hole plates seems to be promising as only one type of reference standards needs to be provided, taught in its use, calibrated and maintained. On the other hand both approaches are limited by the production and especially by the calibration capabilities for small holes/cylinders. The authors see a lower limit in the applicability of both concepts with cylinder diameters of below approximately 0.5 mm. Here the step cylinder concept may earlier focus problems due to the higher aspect ratio of the inner hole of the step cylinder compared to the hole plate as high aspect ratio holes are less easy to calibrate. An additional aspect of the step cylinder/multi-sphere standard concept are questions related to the stability and the calibration capabilities of multi-sphere standards. Even with a well designed multi-sphere standard the authors attribute a hole plate – as a monolithic body – a higher stability compared to a multi-sphere standard which needs to be assembled and mounted.

Manufacturer: Nikon Metrology, Tring, United Kingdom
Model: MCT-225 (manufactured Oct. 2014)
X-ray tube: Reflection target, minimum focus size 3 µm
Mechanics: Cantilever manipulator with three translation axes and rotary axis
Detector: Perkin Elmer XRD 1620 AN3 CS (size 400 mm × 400 mm, 2000 × 2000 pixels)
X-ray source – detector distance: 1174 mm
Acquisition software: Nikon Inspect-X 3.1.9
Reconstruction software: Nikon CT-Pro 3D 3.1.9

Fig. 5. CT system used by PTB.

Table 3
Measurement parameters selected by PTB.

X-ray tube voltage	215 kV
X-ray tube current	54 µA ($\triangleq$ 11.6 W)
No. of projection	1800
Exposure time	2000 ms
X-ray filtration	0.5 mm Copper
Flux normalization	Enabled
Nominal source to object distance	369.06 mm
CT operation mode	Continuous rotation
Measurement time of one CT scan	60 min
Postprocessing of projections	No additional filtering
Nominal voxel size	$(62.9\ \mu\text{m})^3$

5. CT system in use by PTB

PTB used its 225 kV dimensional CT system (Fig. 5) for performing CT measurements. The system specification is declared by the manufacturer to be a unidirectional (centre-centre) length measurement statement: “Accuracy (µm) $\text{MPE}_{(\text{SD})}$: $9+L/50$ (L in mm), for single material samples with a maximum diameter of 250 mm and maximum height of 250 mm”. However, this general CMS “accuracy” for centre-centre length measurements is enhanced for the fixed-magnification measurements in this study by the scaling error correction (cf. section 9) roughly by a factor of three shown below.

6. Measurement parameters selected by PTB

The main objective for the measurement parameter selection was to find parameters which allow all four standards to be measured with the same settings and with the same geometrical properties (same axes positions and thus same magnification). A secondary objective was to minimize the measurement time to achieve measurements acceptable for a future industrial ISO 10360 CT acceptance test. Therefore, the data presented in this report do not represent the best measurement capability (to be applied, e.g., for R&D measurements) of the CT system in use. A constant focus size can be fairly assumed during the whole measurement series, because fixed X-ray tube parameter settings were used and no target burn-in effects were observed during the measurement campaign. For the selected measurement parameters (Table 3) CT measurements are not impaired or limited by the actual extent of the X-ray focus.

7. Observed problems in the ISO test survey

The hole plate (HP) was measured without any enclosure. The NMIJ step cylinder was enclosed in a PMMA housing (sealed by NMIJ) to prevent participants from assessing parts of the geometry by other sensors. Consequently opening the enclosure was prohibited by NMIJ regulation. However, this configuration – having a larger outer diameter (of 75 mm) than the SC (max. diameter 50 mm) and larger height (89 mm instead of 65 mm) – has negative consequences for the test survey. In order to have the setup within the reconstruction field and, to avoid negative artefacts, it was necessary to decrease the magnification. Fig. 6 shows the two projection images of the SC in a tilted setting having the maximum lateral extent. These positions limit the usable magnification. Due to the requirement to perform all measurements with the same magnification [4], the measurements were performed with a magnification, that corresponds to a voxel size of $(62.9\ \mu\text{m})^3$.

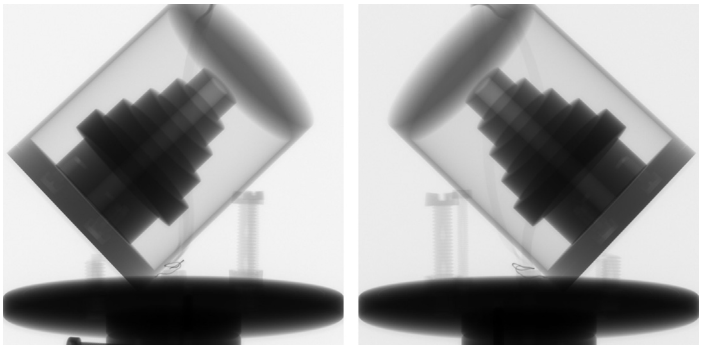

Fig. 6. Two sample CT projection images with maximum lateral extent (in horizontal direction) of the step cylinder standard.

Measurements without the enclosure would allow a twofold higher resolution. The reduced magnification and the enclosure itself may create effects relevant for this test study:

1. Potentially limited sensitivity: Smaller effects may be hidden by the large voxel size.
2. The enclosure material (PMMA) and the aluminium of the SC appear as a multi-material measurement task – this may be relevant for the surface determination. We think that errors are negligible, as there is a significant spatial gap between the SC and the enclosure.
3. BH corrections are usually dedicated to the mono-material case. Thus, the mono-material correction may not work best in the present multi-material case. We think that errors arising are negligible, as the absorption of PMMA is only moderate (significantly lower than aluminium).
4. The enclosure causes absorption and thus influences the measurement parameters to be chosen. We think that errors arising are negligible as the total maximum absorption does not change significantly.

In total, the authors think that mentioned effects have some influence, but can be controlled. Especially the aspect of the large voxel size has to be kept in mind when analyzing and interpreting the data with respect to small effects.

8. Reference values for standards in use

Reference data for the NMIJ step cylinder SC1 was assessed by NMIJ using a tactile CMS. The reference data plus uncertainty statement (expanded measurement uncertainty $U(k = 2)$ of 0.6 µm–0.7 µm) was sent to PTB after submission of PTB raw CT results to ISO/TC 213/WG 10.

PTB assessed reference data for the hole plate PTB Al2 by a tactile CMS. This measurement was performed using a diamond probe 2 mm in diameter. According to [4], ten lengths needed to be measured. These 10 lengths required 20 points to be probed. Each of these 20 “representative points” is assessed as a small “patch” point cloud consisting of five points with an offset in Z (parallel to the cylinder axis) of 0.1 mm. The expanded measurement uncertainty $U(k = 2)$ of the 10 lengths deduced from the provided point calibration table is in the order of 1.0 µm–1.2 µm. No effort was applied to provide a better estimate of the measurement uncertainty, as the effects under study and also the repeatability of CT measurements show a fairly larger magnitude. Also, the voxel size of the CT measurements was $(62.9\ \mu m)^3$ and thus much larger than the uncertainty of the reference data. The tactile CMS data of hole plate PTB Al2 were not used to perform any manipulation of the PTB CT data.

For the multi-sphere standard the reference data of Carl Zeiss was used [8]. The expanded measurement uncertainty $U(k = 2)$ of the calibrated lengths was stated as 1.0 µm.

The PCB centre positions of the single pads were measured by PTB on a calibrated optical CMS two years and also three months prior to use. The observed changes of the PCB board dimensions are input to the measurement uncertainty statement below. In the measured PCB centre positions an equidistant matrix was fitted by the least-squares best-fit method. The free parameters are x- and y-position, the x- and y-scale and the azimuth angle. Thus, the x-scale is the average distance of the pads in direction of the short side of the PCB. Its expanded relative uncertainty $U(k = 2)$ is $4.6 \cdot 10^{-5}$. Thus, the expanded scaling uncertainty for a 50 mm object can be estimated as 2.3 µm.

9. Measurement scheme applied by PTB

The CT system was used in a precorrected state. For a correction of the residual scaling factor, additional measurements were performed using the PCB and the MS standard data. The measurement sequence chosen starts and ends with a quick 2D reversal measurement of the PCB (Fig. 7) and a CT measurement of the MS standard (Fig. 8). The hole plate HP and the step cylinder SC were measured in a 0° vertical position (Fig. 2, left) and in a 45° tilted position (Fig. 2, right). This scheme was repeated on a second day. The whole measurement series was performed within 34 hours, with a 15 hour break. Thus, the measurement sequence in a nearly symmetric scheme was:

PCB, MS, HP0°, HP45°, SC0°, SC45°, PCB, MS; 15 h break; PCB, MS, HP0°, HP45°, SC45°, SC0°, PCB, MS

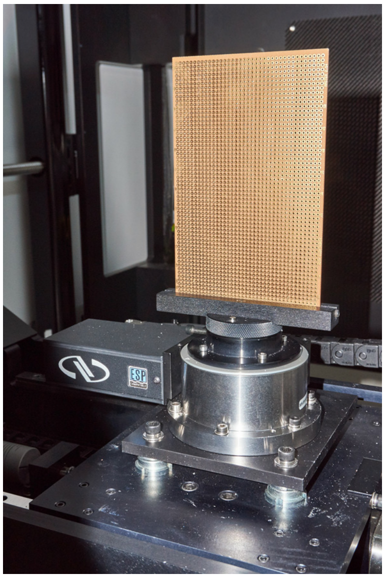

Fig. 7. Printed circuited board during projection measurement.

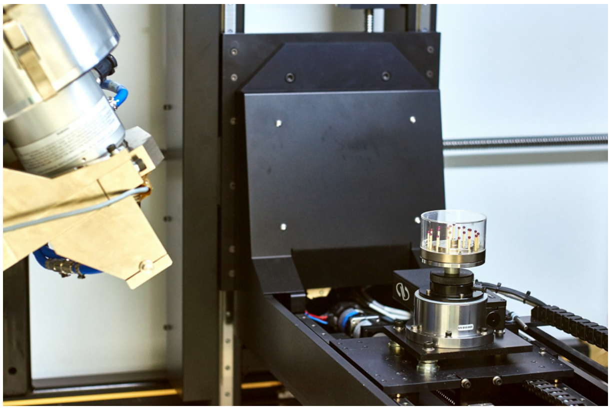

Fig. 8. CT measurement of the multi-sphere standard.

All measurements were performed using the same measurement parameters. Additionally, to ensure comparability, measurements were performed at a constant magnification without movement of any mechanical axes and with permanent, constant focus coil current. Before the start of the series, a high-quality shading correction of the detector (not only flat-field/offset-gain correction, but performed as a 6-point multi-point correction applying 256 images for each exposure setting) was created and then used for the 34-hour series.

All data has been checked for consistency. No negative effects have been observed which may have entered due to the long time use of one fixed shading-correction. No significant drift (movement) of the objects during the CT scanning or ring artefacts or other negative effects were observed.

The PCB was measured using two 180° reversed projection images with the PCB perpendicular to the magnification axis (better than 1/20°). The integration time for each of the two PCB images was 128 s. With a pattern-recognition software the pad positions can be determined for both images and, subsequently, an equidistant matrix can be fitted (here an additional parameter for trapezoidal distortion caused by the rotary axis tilt has to be considered). The harmonic mean of the x-scales of the images in reverted orientation is the x-scale at the position of the rotary axis. This has to be compared to the x-scale from the PCB's calibration. As one pixel of the detector is directly translated to one voxel in the volume by the reconstruction software, the scale can be concluded. [9] contains more detailed guidance on how the PCB data were assessed.

10. Measurement data processing

The reconstruction of the projections was performed using the software Nikon Metrology CT-Pro 3D 3.1.9. The following parameters were used:

1. Reconstruction without beam hardening (BH) correction (preset 1 of CT-Pro 3D), and

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2. Reconstruction with second order polynomial BH correction (preset 2 of CT-Pro 3D). This (static) BH correction was applied to the HP and to the SC data. An individual correction is possible, but was not performed here.

All projection data were reconstructed as float data using the Hanning filter inside the reconstruction (this setting corresponds to preset 2, which is the least noise suppressing preset). The use of this filter is appropriate for the measurands under study and the characteristics of the data assessed. Further 3D data analysis was performed using Volume Graphics VGStudio Max 2.2.6. No posterior filtering was performed on the 3D grey value volumes before surface determination. "Advanced" surface determination mode was used without any further modifications. No morphological filtering was applied in the surface determination step. By using point clouds with nominal point data in the coordinate system as defined in [4], points were measured on the surface. By using this approach point probing in CT and tactile CMS reference point probing use nominally the same strategy. For creating the coordinate system, planes and cylinders were fitted to the CT data of HP and SC. The nominal point data input consists of point coordinates (x, y, z) and nominal probing vectors (n_x, n_y, n_z). The analyses were performed using templates for each standard under study. To this end, an alignment of the template relative to the part was performed. After "probing" the points, all measured points were exported for data analysis using a spreadsheet software. In this software the respective averaging of the five points of the single patches and the final length analysis were performed. The data analysis procedure for the PCB and the deduction of the scaling factor were carried out as described above. For using the tactile CMS reference data of [8], all 35 lengths stated in the certificate of the MS standard are exploited for the least-squares fitting of a linear scaling factor. Both scaling error analysis methods (MS, PCB) result in a scalar scaling factor to be applied to all lengths. PTB submitted the data for the assessed 10 lengths of hole plate PTB Al2 and also step cylinder NMIJ SC1 to ISO/TC 213/WG 10. The submission contained data for the two angular settings (two measurements each) and also data with and without the MS-based scaling correction. The dataset contained lengths being assessed without BH correction and with BH correction. In total, 160 lengths were reported for the HP and 160 lengths for the SC. There was no statement as to which data is declared as the best measurement state (as this was outside the scope of the test survey).

11. Measurement results

Residual scaling error:

Residual scaling error analysis was performed using the multi-sphere (MS) standard and as well the PCB data. The maximum centre-centre length measurement error recorded using the MS standard was −13.5 µm. The total variation of length measurement errors for the five different nominal lengths assessed on the MS standard was between ±0.7 µm and ±1.4 µm at maximum, while the range of single lengths (i.e. repeatability) was between 0.1 µm and 0.9 µm. This shows that the residual errors of the CT system in use for standards like the MS standard are dominated by a residual scaling factor. The resulting scaling factors from using the unidirectional length measurement errors observed with the MS standard in the sequence of measurements are: 1.000222, 1.000219, 1.000218 and 1.000218 with an average of $k_{\mathrm{sc}}^{\mathrm{MS}} := 1.000219$. CT is measuring too short. Thus, all lengths have to be multiplied by this factor. The scaling correction factors resulting from the unidirectional length measurement errors observed with the PCB in the sequence of measurements are: 1.000149, 1.000166, 1.000130, 1.000157 with an average of $k_{\mathrm{sc}}^{\mathrm{PCB}} := 1.000150$. Due to the fact that two different scaling factors were assessed, the authors decided – as the absorbing material of the PCB is copper instead of aluminium – to use in this test study only the scaling correction factor $k_{\mathrm{sc}}^{\mathrm{MS}}$. $k_{\mathrm{sc}}^{\mathrm{PCB}}$ is stated here for documentation only. The relative difference of $k_{\mathrm{sc}}^{\mathrm{MS}}$ and $k_{\mathrm{sc}}^{\mathrm{PCB}}$ of 31% might be a hint of a material-dependent systematic effect.

Direct observation related to the single measurement results of HP and SC:

The repeatability of the CT is a function of the measurement parameters selected and of the operator which is applied to create the "representative point" from single point measurements in the neighbourhood of a nominal point. In this test survey, the operator uses only five points. Thus, some differences are observed between the first and the second measurement of HP and SC. The differences are 10 µm at maximum. Most of the measured lengths are repeated within 2–3 µm. These differences are below 5% of the voxel size in use and are much smaller than the systematic effects observed (showing effects up to 45% of the voxel size). By using the average of the two measurements, the effects of the reproducibility are reduced even more. Only the averaged data will enter into the final interpretation (see the following).

Results of averaged measurements of HP and SC:

The following diagrams (Figs. 9–16) show the results of averaging the lengths of two measurements. Pairs of measurements are presented – HP measurements and SC measurements – which are evaluated using the same workflow. All diagrams feature the bidirectional length measurement error as a function of the length L to be measured. Angular statements 0° and 45° refer to measurement positions visible in Fig. 2, while "inner" and "outer" refer to measurement lengths 1–5 (being inner lengths) and 6–10 (being outer lengths), respectively (cf. Figs. 3–4 and Tables 1–2). Data point symbol "cross" is used for inner length measurements, while a "triangle" symbol represents an outer length measurement. In addition, Fig. 10 shows for comparison the edge length of one voxel of the measurements performed (see green arrow).

Direct observation related to the averaged measurement results:

The MS-based residual scaling error correction was successful in most cases decreasing the range of errors and in most cases in reducing the largest errors. The nearly horizontal direction of the HP and also the SC data shows that there is no strong residual length-dependent error for the scale corrected measurements. Nevertheless, a slight overcompensation can be observed – also in comparison to the PCB-based correction: It can be seen that there may be a residual linear

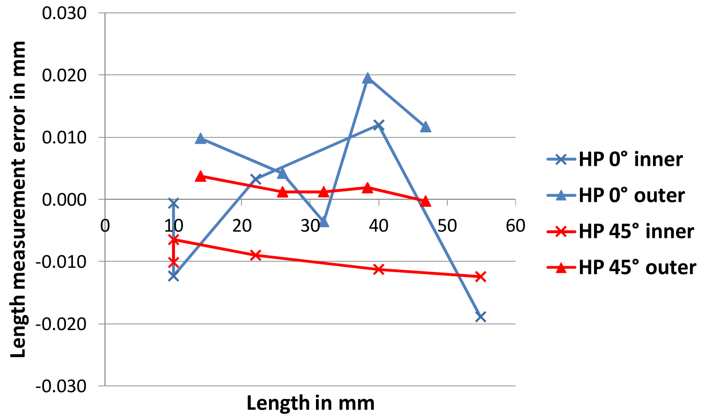

Fig. 9. Length measurement errors for hole plate PTB Al2. BH correction switched off; scaling error correction switched off.

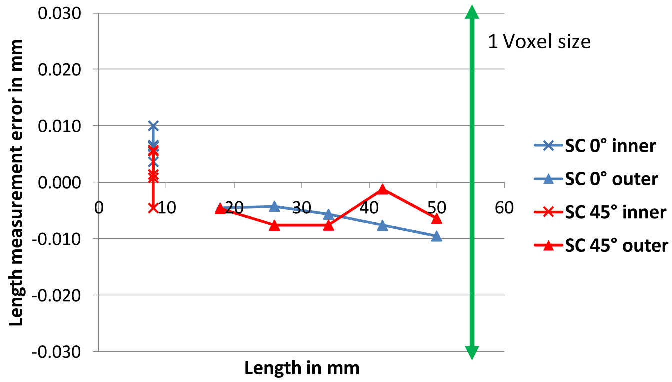

Fig. 10. Length measurement errors for step cylinder NMIJ SC1. BH correction switched off; scaling error correction switched off.

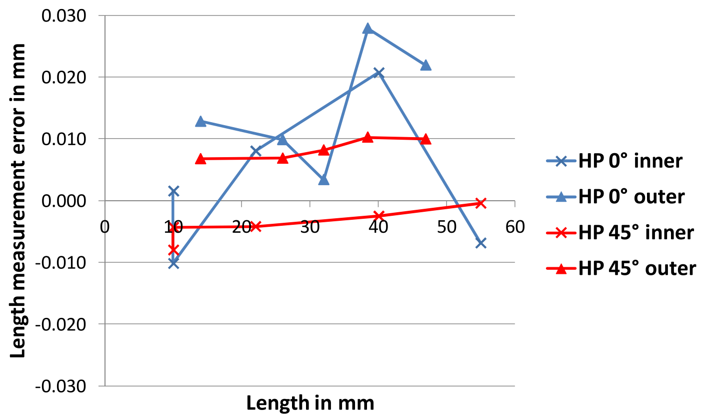

Fig. 11. Length measurement errors for hole plate PTB Al2. BH correction switched off; scaling error correction switched on.

dependence after the performed scaling correction of roughly 3 µm at maximum for the longest length of 56.5 mm. This error is by a factor of three less than the accuracy statement of the manufacturer (cf. section 5), which was shown by the MS standard measurements to be dominated by the scaling error. In total, the scaling error influence in this test survey is low in comparison to other influences observed, e.g. BH-related effects. There is also no dependence of the observed errors in the step diameter for the case of the SC. This can be seen from the alternative presentations of Figs. 17–20.

The differences between the errors of inner and outer lengths for the HP are in the order of 10–12 µm in absence of a BH correction. The differences shrink to about 5 µm when the BH correction is switched on (compare Figs. 9 and 13 and as well 11 and 15; but this is only a rough estimate, as lengths and position of lengths on the standard are different for inner and outer lengths). Consequently, a potential error in the surface determination procedure caused, e.g., by manually

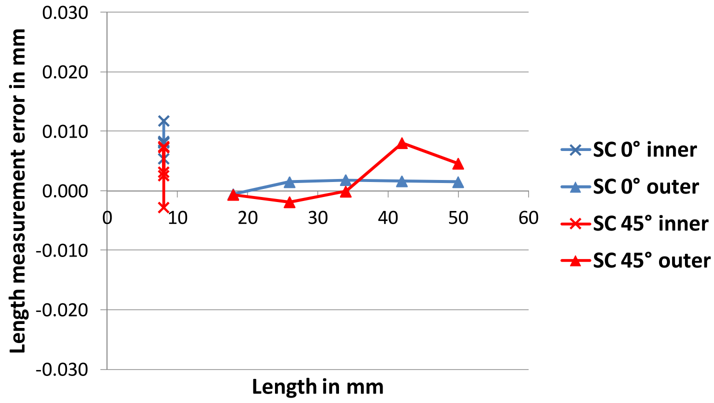

Fig. 12. Length measurement errors for step cylinder NMIJ SC1. BH correction switched off; scaling error correction switched on.

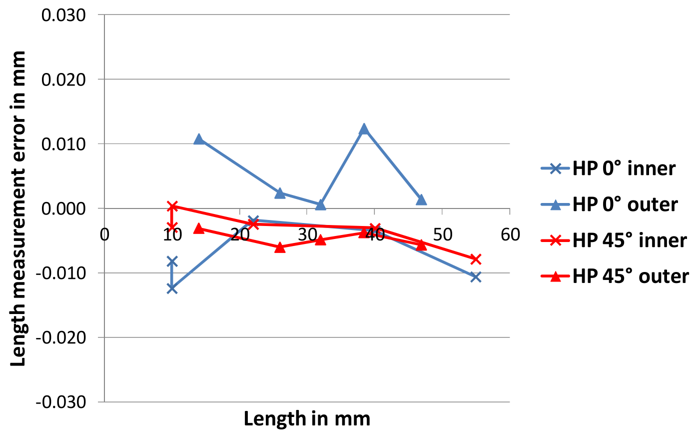

Fig. 13. Length measurement errors for hole plate PTB Al2. BH correction switched on; scaling error correction switched off.

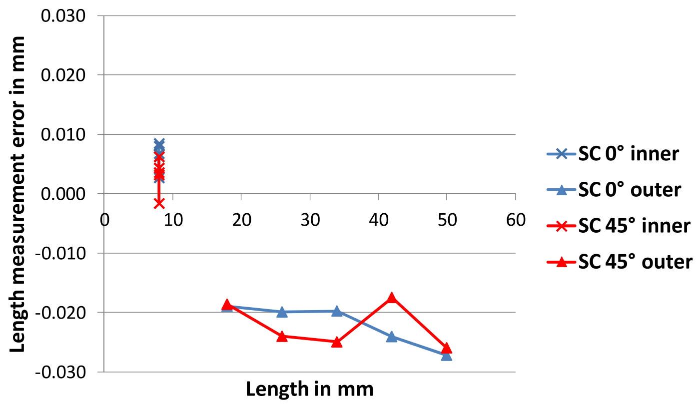

Fig. 14. Length measurement errors for step cylinder NMIJ SC1. BH correction switched on; scaling error correction switched off.

setting the threshold start parameter in the "advanced" mode surface finding procedure (cf. section 10) appears to be small, especially when compared to BH-related effects.

The differences between the length measurement errors of inner and outer lengths for the SC are in the order of 5–10 μm in absence of a BH correction. Consequently, a potential threshold-dependent error – as described above – appears to be small, too. Switching on a static BH correction enlarges these differences to 20–25 μm! This "splitting effect" is clearly visible at all outer lengths even if these lengths are very different. The effect appears to be of a systematic nature and causes a constant offset error in the order of 1/3 voxel (20 μm).

To summarize, the data show an improvement due to the BH correction for the hole plate (span of error decreased by 35%) but a degradation due to the BH correction for the step cylinder.

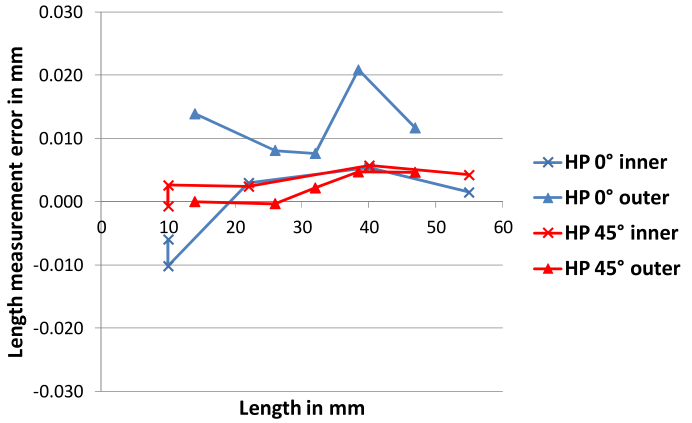

Fig. 15. Length measurement errors for hole plate PTB Al2. BH correction switched on; scaling error correction switched on.

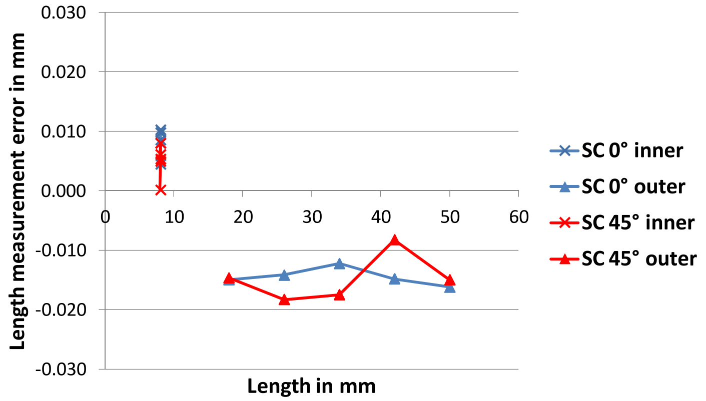

Fig. 16. Length measurement errors for step cylinder NMIJ SC1. BH correction switched on; scaling error correction switched on.

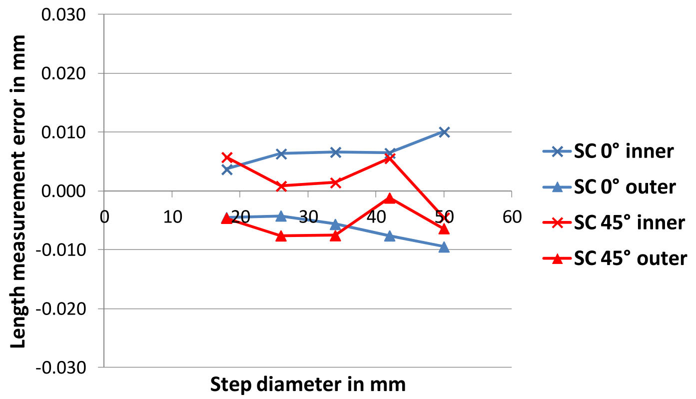

Fig. 17. Alternative presentation of length measurement errors for step cylinder NMIJ SC1 (cf. Fig. 10). BH correction switched off; scaling error correction switched off.

The overall largest absolute measurement error at the HP (28 μm ≙ 45% of voxel size) occurred when using the BH correction switched off and additional scaling correction switched on. The overall largest absolute measurement error at the SC (27 μm ≙ 43% of voxel size) occurred when using the BH correction switched on and no additional scaling correction.

An examination of the SC X-ray penetration by the authors shows that there is always a large difference between the X-ray penetration lengths through the inner bore hole and the outer cylinder: Relevant regions of the projections which contribute to the reconstruction of the inner bore hole feature long penetration lengths whereas short and medium length penetrations contribute for the outer cylinder edges. This is the case for the 0° vertical position and also for the 45° tilted position. For this reason the SC geometry appears to be unusual and is in our opinion not comparable to many technical workpieces – where CT measurements usually require long and also short penetration lengths to be assessed. The

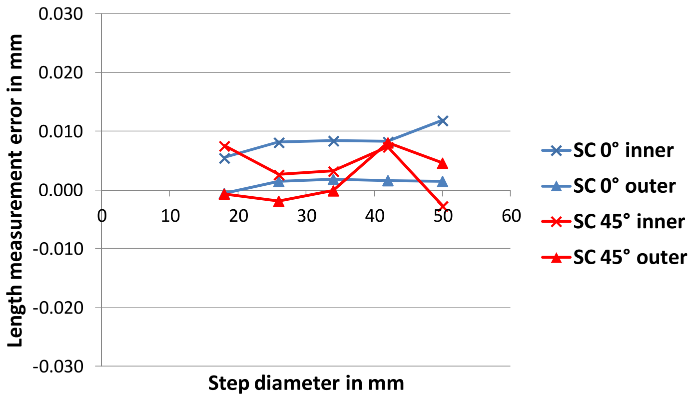

Fig. 18. Alternative presentation of length measurement errors for step cylinder NMIJ SC1 (cf. Fig. 12). BH correction switched off; scaling error correction switched on.

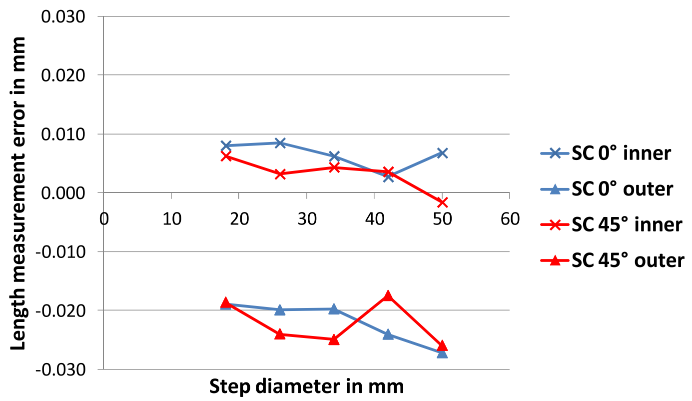

Fig. 19. Alternative presentation of length measurement errors for step cylinder NMIJ SC1 (cf. Fig. 14). BH correction switched on; scaling error correction switched off.

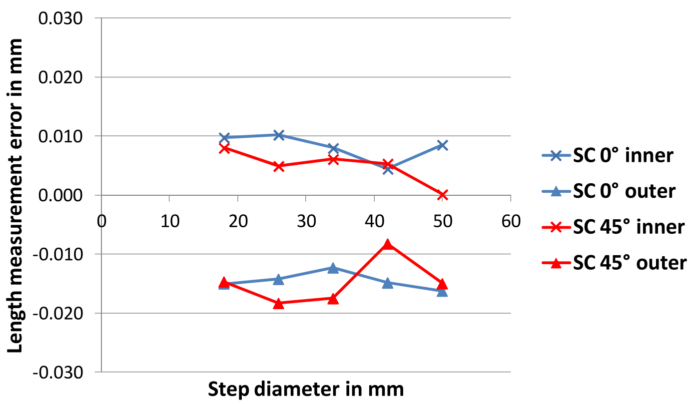

Fig. 20. Alternative presentation of length measurement errors for step cylinder NMIJ SC1 (cf. Fig. 16). BH correction switched on; scaling error correction switched on.

consequences of this specific penetration can be seen from radial grey level profiles (in the reconstructed volume) through the bore hole and the outer surface when applying a BH correction of increasing strength. The inner bore hole grey profile edge remains nearly unchanged even for strong BH corrections while the outer diameter edge is strongly affected even by small corrections. For the SC geometry, in total, the "no BH correction" case – in contrast to expectations for ordinary workpieces – leads to the lowest deviations. Thus, the BH correction capability of the CT-based CMS, which is relevant for workpiece measurements stays untested.

12. Measurement data interpretation of PTB with respect to future ISO 10360 testing for CT

The objective of this ISO/TC 213/WG 10 test survey was to answer the following questions (cf. [4]):

1. *Is it possible to quantify the material thickness influence on the assessed data?*
PTB: Yes, it was possible to assess material thickness-dependent effects using the hole plate (HP) in two angular positions. These effects become visible when comparing observed bidirectional length measurement errors with unidirectional (centre-centre) length measurements of the multi-sphere (MS) standard. The effects observed for the HP shrink when a proper beam hardening (BH) correction is used – this is a further indication for material thickness-dependent effects. For the step cylinder (SC), a material thickness dependence can be observed, too. However, the behaviour appears to be inconsistent. See answer to last question.
2. *Is the material thickness effect assessed in a sufficient way by using the standards under study?* (*sensitivity of the standards under study related to CT specific material thickness effects*)
PTB: Yes, the magnitude of effects and the bidirectional length measurement errors observed with the HP and the SC appears to be realistic. In particular, this magnitude is larger than the errors which are assessed by the MS standard when measuring unidirectional length measurement errors (factor of two between maximum errors assessed with the MS standard and with either the HP and the SC).
3. *Are there other proposals*, e.g., *for using other standards?*
PTB: No, not now.
4. *Comment on problems which were observed.*
PTB: The sensitivity of the test survey appears to be slightly degraded due to the enlarged voxel size (resulting from the enclosure of the SC). In total, we don't think that this slight loss impairs the results of the test survey.
5. *Which standard is recommended after also considering other aspects* (e.g. *simplicity of use, price, calibration costs, etc.*)?
PTB: We recommend technically the use of the HP for measuring bidirectional length measurement errors E including sufficient material thickness effects (see answer to first question). In the case of the SC the geometry does not appear to be realistic enough to represent the measurement of workpieces due to the high symmetry of this standard. The use of the SC may create a wrong impression of corrections dedicated to improve measurements of real workpieces, as it may lead to "embellished" results. Testers who are aware of the dependence observed in this test survey could perform measurements with the BH correction switched off. Consequently, the capability of the CT system to measure real workpieces including material thickness influences (where a BH effect usually is observed and needs to be corrected) remains untested. For the assessment of the length measurement errors, the position of Fig. 2, left (HP is in a lying position, HP cylinders are parallel to axis of rotation), seems to be of interest as the largest error is observed. The tester should be free to use this position for testing. Due to the further disadvantages of the SC, being an additional standard to for example a MS standard, causing additional total measurement effort and costs, PTB finally recommends to use only the hole plate for assessing bidirectional length measurement errors of CT at least for hole plates featuring holes of diameter of about 0.5 mm and above (or other standards providing the same advantages). It would be helpful to confirm the experimental results described here with simulation aided studies to further confirm the observed effects, especially in the case of the SC geometry. For the domain of micro CT where small measuring field sizes require the use of extremely small reference standards the authors do not see applicability of neither step cylinders nor hole plates as manufacturing and especially calibration capabilities of holes below e.g. 0.5 mm in diameter cause severe restrictions for industrial use.

Further analysis of the participant PTB:

The experiences of PTB within this ISO/TC 213/WG 10 test study stimulate further reflection about the type of the measurands assessed with HP and SC, both being curved, non-planar geometries. At the moment we recommend not using *single points* to create "representative points" for assessing length measurement errors from two nominal surface points. The balanced choice of boundary conditions for proper patch operators to create "representative" points (i.e. a framework for applicable operators) appears to be a future objective in ISO/TC 213/WG 10 task force CT for creating an ISO 10360 part for CT. No strong differences were observed for inner and outer length measurements for the MS and the SC for respective best measured states. It is concluded that there is no significant threshold-dependent error left over. Furthermore, there is no significant linear dependence of the errors from the measured length after scale correction. The difference between the two residual scaling errors which were assessed in this study by PTB appears small in relation to the other effects under study. It is to be stressed that the magnitude of all observed bidirectional length measurement errors were below 50% of the voxel size and dropped down to 20% of the voxel size for the best corrected measurements – which is a very satisfying result. This is a remarkable indication for achievable low level residual length measurement errors, which can be observed with current state of the art CT systems.

Acknowledgements

The authors thank the National Metrology Institute of Japan NMIJ, AIST, Japan for providing calibrated step cylinders for this ISO test survey, and Carl Zeiss, Oberkochen, Germany for providing PTB with a calibrated multi-sphere reference standard. The authors thank Uwe Langner and also Astrid Linkogel and Konrad Hierse, (all PTB), for performing tactile reference and verification measurements of hole plates.

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